Assessment of recycled concrete aggregates as a pavement material

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Abstract. Population increase and economic developments can lead to construction as well as demolition of infrastructures such as buildings, bridges, roads, etc resulting in used concrete as a primary waste product. Recycling of waste concrete to obtain the recycled concrete aggregates (RCA) for base and/or sub-base materials in road construction is a foremost application to be promoted to gain economical and sustainability benefits. As the mortar, bricks, glass and reclaimed asphalt pavement (RAP) present as constituents in RCA, it exhibits inconsistent properties and performance. In this study, six different types of RCA samples were subjected classification tests such as particle size distribution, plasticity, compaction test, unconfined compressive strength (UCS) and California bearing ratio (CBR) tests. Results were compared with those of the standard road materials used in Queensland, Australia. It was found that material type 'RM1-100/RM3-0' and 'RM1-80/RM3-20' samples are in the margin of the minimum required specifications of base materials used for high volume unbound granular roads while others are lower than that the minimum requirement.

Keywords: Recycling; Waste concrete; Road materials; Classification tests

1. Introduction

Demolished materials are becoming more popular to be recycled and reused due to shortage of natural mineral resources, increasing waste disposal cost, and increasing the demand of materials. Conversely supplying the conventional aggregates for construction purposes make impact on resource depletion, environmental degradation, and energy consumption. Therefore reusing the recycled materials creates many economical and environmental benefits.

Crushed concrete can be considered and promoted as an alternative and a sustainable source of aggregate for construction industry. Studies have revealed that recycled concrete aggregates can be applied as a partial or complete substitution of natural aggregates in the production of ordinary concrete (Amnon 2003, Poon *et al.* 2004, Kou *et al.* 2011). Ismail and Ramli (2013) tested the effect of using different molarities of acid solvent and age of treatment (soaking) on properties of

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RCA in concrete structures. Their result was the use of treated RCA made higher compressive strength as compared to untreated RCA in concretes. Butler *et al.* (2011) Focused his studies on RCA to evaluate the bond strength between RCA concrete and steel reinforcement and conclusion was to consider RCA as an alternative coarse aggregate to use in structural concrete applications. However, Hansen (1992) found that fine portion of RCA makes detrimental effects on the harden properties of concrete; thus coarse RCA is best to reuse for concrete.

The studies on RCA as pavement material have been widely reported in the last decade. Poon and Chan (2006) reported the feasibility of using RCA blended with crushed clay bricks as materials to produce sub-bases. His samples had the minimum required strength according to Hong Kong specifications. Park (2003) introduced RCA as base and sub-base material for concrete pavement. Nataatmadja and Tan (2001) used high strength concrete to produce RCA at the laboratory and conducted repeated load tri-axial test to investigate the resilient response of RCA. Based on the test results they assumed the performance of the base and sub-base materials prepared with both coarse and fine RCA were comparable to that of conventional base and sub-base materials. Chini *et al.*(2001) conducted a research in the United State to assess the feasibility of using RCA as a base material layer under hot mix asphalts and as an aggregate in portland cement concrete pavement. This research was confirmed the requirement of future research on RCA and the need of a practical guide for the use of RCA in pavement construction. This guide can be used by the producers and users of RCA prior to make popular it as a pavement aggregate.

Although these research findings have demonstrated the feasibility of using RCA as sub-base material as well as for base course of the concrete pavements, a detailed investigation of RCA as base and sub-base material for unbound granular pavements is required. These investigations should include determining the classification properties of RCA considering the variability of its compositions and performance characteristics under repeated loading. Evaluation of the performance of a granular pavement constructed using RCA is the best way to investigate the deformation criteria in real traffic loading under different climatic conditions. As the first step of such a detailed investigation on RCA, this paper presents the results of classification tests of six different RCA samples. The results have been analysed to examine the feasibility of using RCA in unbound granular pavement construction by comparing their classification properties with those of the conventional unbound granular materials used in the state of Queensland, Australia.

2. Materials Used

For this study, two primary commercially available RCA products, named as RM001 and RM003 (see Fig. 1) were obtained from a leading concrete recycling plant in Queensland. Material sources are demolished building (slabs, floors, columns and foundations), bridge supports, airport runways and concrete road beds. The collected source materials went through specified crushing process to produce RM001 and RM003. Table 1 shows the maximum percentages of the constituents that can be permitted in RM001 and RM003 at the plant output. RM 001 is produced by crushing only the waste concrete which is separated from other demolished waste to avoid mixing other constitutes such as bricks, asphalt, glass etc. In the process of producing RM003 bricks and RAP are allowed but controlled for their maximum allowable percentages. Figs. 1 (a)-(b) show the photos of the two crushed RCA products.

These two materials were blended in different percentages by weight to form another four samples to represent various combinations of constituents. New sample types with their blending percentages are showing in Table 2.

(a) (b)

Fig. 1 RCA materials (a) RM001 and (b) RM003

Table 1 Percentage limits of constituents of two main RCA materials

Recycled Material Type	Maximum Limit of each Constituent (Percentage by mass)		
	Reclaimed Concrete	*RAP	Brick
RM001	100	-	-
RM003	100	20	15

*RAP – Reclaimed Asphalt Pavement

3. Laboratory Testing, Results and Discussion

RCAs are highly heterogeneous and consist of different amounts of impurities and their quantities are not steady. Therefore RCA can have inconsistent classification and strength properties and it is essential to check the properties of RCAs through classifications and strength tests. In this study sieve analysis test, atterberg limits test, proctor compaction test and strength test such as California bearing ratio (CBR) and unconfined compressive strength (UCS) tests were performed on each RCA sample shown in Table 2 to investigate the possible range of variation of classification and strength parameters. The results were then compared with the specifications of standard base and sub-base materials recommended by Department of Transport and Main Roads in Queensland. These standard materials types are shown in Table 3 with their descriptions (MainRoads 2009).

Table 2 New RCA samples with blending percentages

Material name	Mixing percentages by mass (%)	
	RM001	RM003
RM1-100/RM3-0	100	0
RM1-80/RM3-20	80	20
RM1-60/RM3-40	60	40
RM1-40/RM3-60	40	60
RM1-20/RM3-80	20	80
RM1-0/RM3-100	0	100

Table 3 Standard pavement materials with their description

Material Type	Pavement layer	CBR (Soaked) –Minimum %	Description
2.1	Base	80	Roads with design traffic equal to or exceeding 10^6 equivalent standard axle (ESA) repetitions
2.2	Base	60	Roads with design traffic less than 10^6 ESAs
2.3	Sub-base	45	Roads with design traffic equal to or exceeding 10^6
2.4	Sub-base	35	Roads with design traffic less than 10^6 ESAs
2.5	Lower Sub-base	15	Roads with design traffic less than 10^6 ESAs

3.1 Particle Size Distribution

Particle size distribution (PSD) of a particular pavement aggregate type affects its compressibility, permeability, density, etc (Papagiannakis and Masad 2008). Therefore gradation of a pavement material has to be checked continuously to maintain the required particle size and quantities. The primary materials RM001 and RM003 had maximum particle size 25.4 mm and 19 mm respectively. To determine the gradation of mixed RCA samples, dry sieve analysis was performed according to the Australian standards (Australia 2009a). Fig. 2 shows the PSD curves for six RCA samples having reasonably well graded distribution. However, the comparison of the six gradation curves with 'Material type 2.1' appears that the grading limits of all RCA samples are within the shortage of coarse particles and do not fulfil even the lower bound of Material type 2.1 (which indicates the low percentage of coarse particles). Material Type 2.1 is presented the standard specification for base layer material in high traffic volume roads by the Department of Transport and Main Roads, Queensland, Australia (see Table 3). The lower coarse aggregates results in comparatively low strength in compacted material and low bearing capacity due to the weak imparting strength among the particles.

Breaking of materials under compaction is significant for the volume stability of a particular pavement layer in unbound granular pavements. Breakdown of individual particles under the traffic loading can alter the grading of the materials and lead to changes in density (Youdale and Sharp 2007). Fig. 3 shows the PSD curves prior to and after compaction for each sample. Fig. 4 shows the PSD results after compaction for the six samples together with lower and upper bound of Material type 2.1. The grading curves of the Figs. 3-4 indicate that breakdown occurred under the compaction in all samples. They show comparatively higher response for breaking particles under compaction in ‘RM1-100/RM3-0’ and ‘RM1-80/RM3-20’ since it is likely that breakdown occurred in aggregates when high percentage of RM001 material that has more coarse aggregates. With the increasing of RM003 portion in other samples the breakdown has been less since the percentage of aggregates is low. It is clearly notable that there is reduction of coarse particles and increasing fines after compaction.

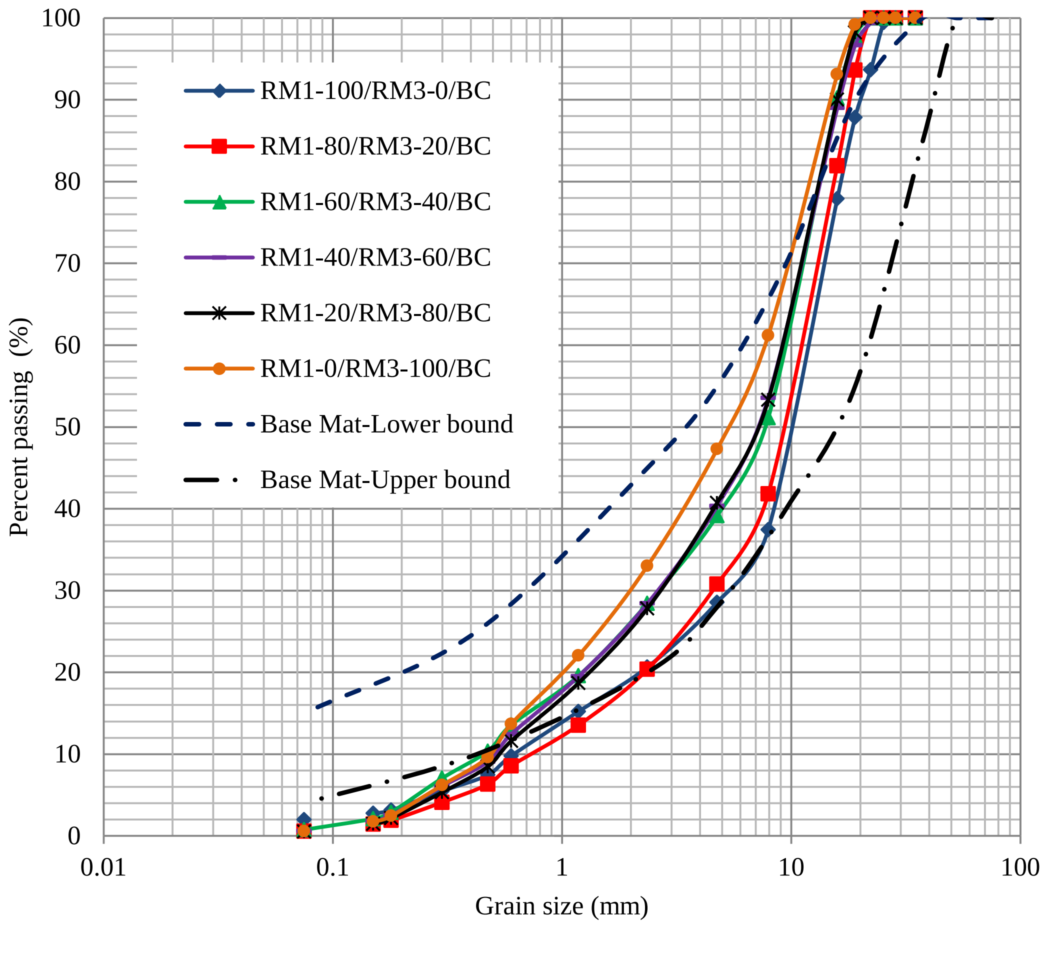

Fig. 2 Gradation curves for six samples and maximum & minimum curves of subtype 2.1 materials

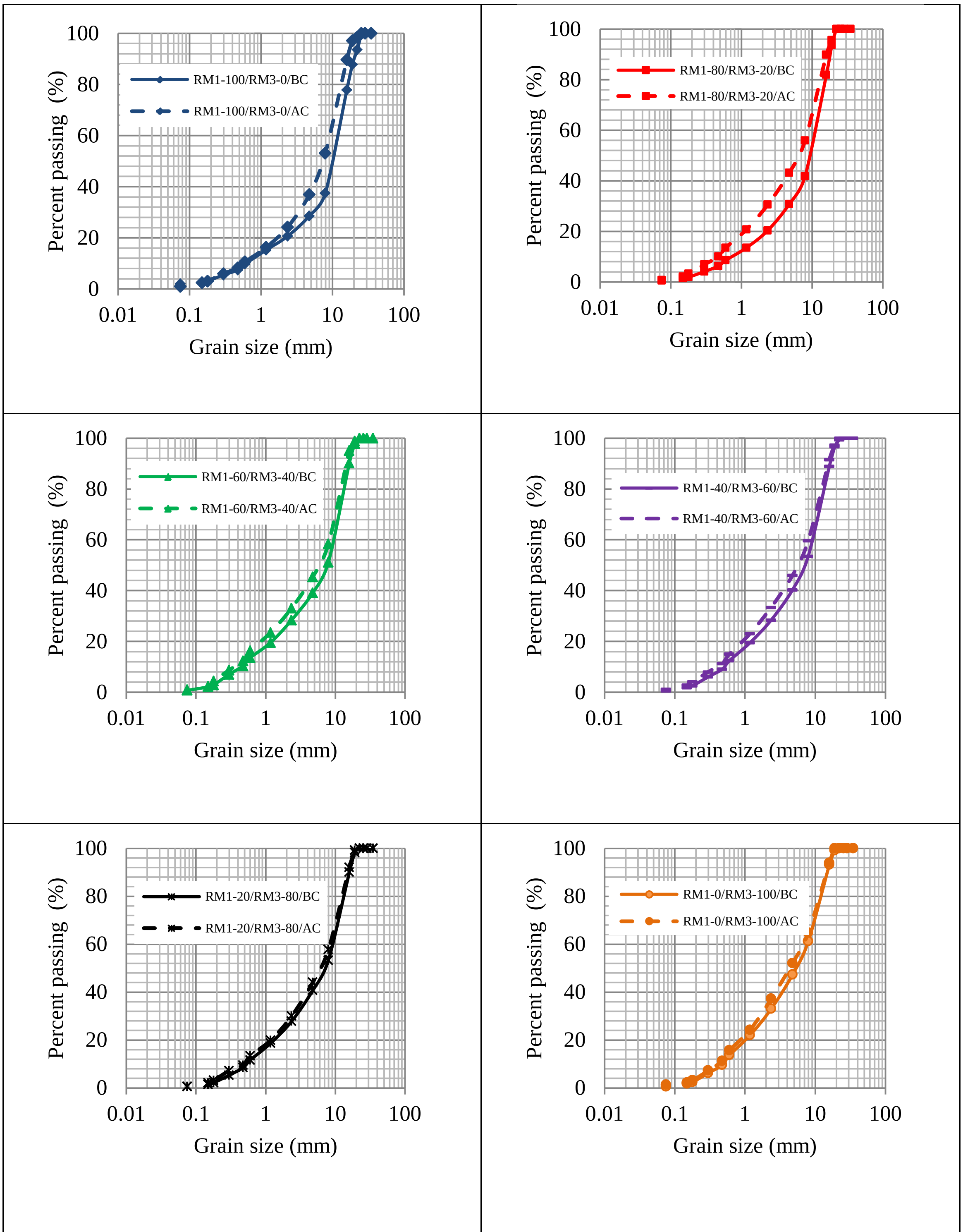

Fig. 3 Gradation curves for six samples prior to and after compaction

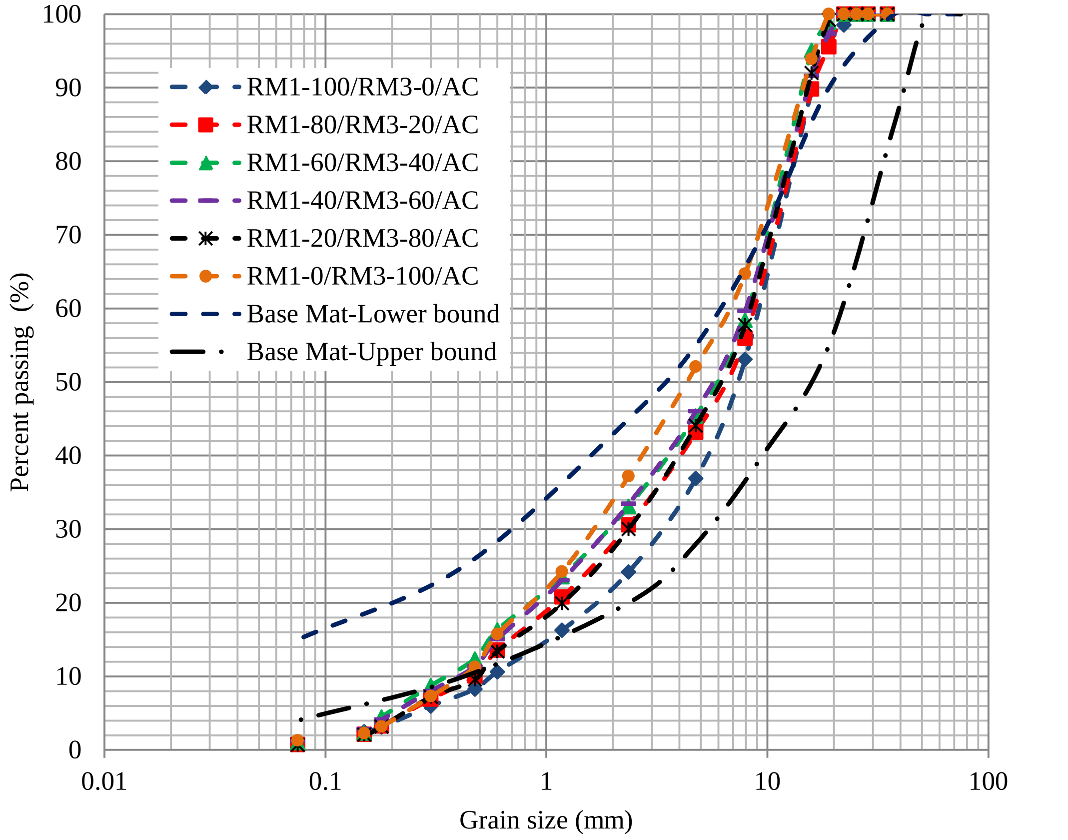

Fig. 4 Gradation curves for six samples after compaction with maximum & minimum curves of subtype 2.1 materials

3.2 Plasticity

Determining the plastic properties of materials is very important since the plasticity affects shear strength, modulus, permeability, etc of compacted materials. The plasticity index reflects the range of moisture content over which the material is susceptible to compaction by external forces (Aksakal *et al.* 2013) and depict the expansive nature of a particular material (Voung *et al.* 2008).

Liquid limit (LL) and plastic limit (PL) test were conducted for fines passing 0.475 mm sieve according to the Australian standards (Australia 2002, Australia 2009b). Fines of only 'RM1-100/RM3-0' and 'RM1-0/RM3-100' were tested since other four samples are blended using these two fines. The LL values and mean values of PL test are summarized in Table 4. According to the Department of Main Roads, Queensland specifications; the maximum plasticity index (PI) is 6 for material subtype 2.1(See Table 3). 'RM1-100/RM3-0' is within that range but 'RM1-0/RM3-100'having PI of material subtype 2.3 which is given maximum PI as 8. The subtype 2.3 has been recommended for upper sub-base layers by Main Roads (MainRoads 2010). However, RCA fines are showing plastic properties similar to the high quality pavement aggregates such as crushed Rhyolite (PI=6) and crushed Hornfels (PI=8) (Jameson *et al.* 2010). The low plastic properties of RCA's fines decrease the workable range of the materials leading low susceptibility for compaction.

Table 4 Plasticity Index of two main materials

Fine Sample	RM1-100/RM3-0	RM1-0/RM3-100
LL	21	27
PL	15.6	20
PI	5.4	7

3.3 Compaction

The moisture density curve (compaction curve) of a soil is an indicator of the sensitivity of the density with respect to the variation of moisture content in the materials (Poon *et al.* 2005). Materials with flat curves can tolerate a greater amount of variations in the moisture content without compromising much of the achieved density from compaction. In contrast, materials with sharp curves are extremely sensitive to the optimum value during compaction.

Table 5 Optimum Moisture Content and Maximum Dry Density for Six Samples

Sample Type	Optimum Moisture Content %	Maximum Dry density (t/m^3)
RM1-100/RM3-0	13.2	1.748
RM1-80/RM3-20	13.2	1.768
RM1-60/RM3-40	13.3	1.822
RM1-40/RM3-60	13.5	1.856
RM1-20/RM3-80	14.0	1.836
RM1-0/RM3-100	14.2	1.846

Standard proctor compaction test in accordance with Australian Standards, AS 1289.5.1-2003 (Australia 2003) was performed on each testing sample and the results of optimum moisture content (OMC) and maximum dry density (MDD) values of each material is tabulated in Table 5. The range of the variation of MDD and OMC are relatively small as 1.748-1.856 t/m^3 and 13.2-14.2%, respectively. It can be seen that with the increase in RAP and brick fines contents of samples, they tend to well compacted. Both OMC and MDD increase as fines can absorb more water and reduce the void volume by filling the voids between larger particles. However all the RCA samples show comparatively higher OMCs and lower MDDs than the high quality crushed pavement aggregates like Rhyolite (5.85%, 2.34 t/m^3), Hornfels (6.5 %, 2.32 t/m^3), Limestones (6.5%, 2.34 t/m^3) which the corresponding OMC and MDD are shown in brackets (Jameson *et al.* 2010). The main reason for the higher water absorption is the presents of cement fines and other constituents like bricks. In addition, the aggregates have been subjected two crushing processes (Initial crushing after the mining and second crushing process at the recycling concrete structures) and therefore the stiffness of the aggregates become lower. This cause for easily breakage of the materials and add more fines at the compaction. Therefore, lack of coarser particles and higher constituents led for lower bulk density and thus for lower MDDs in RCA samples.

3.4 California Bearing Ratio tests

Rutting and shoving are the major defects in pavement surface due to the shear failure in base and sub-base layers. CBR test provides an indicator of the shear strength of materials since the compacted materials subject to shear deformation (Voung *et al.* 2008). Therefore CBR characterization is widely used in pavement industry to provide a relative measure of strength, elastic modulus and moisture durability across various road materials for structural design purposes (Papagiannakis and Masad 2008).

CBR tests were performed as specified in AS 1289.6.1.1 – 1998 (Australia 1998) on the six samples. Even though the samples were mixed with water at their corresponding OMCs values, the achieved moisture contents were over the OMCs levels. This is due to the high inconsistency of the sand and cement fines as well as varying the constituents content (RAP and brick contents are varying between 0-20 and 0-15 % respectively in RM003-see Table 1). Therefore it was very complicated to maintain exact moisture content in the samples. Figs. 5(a)-(b) show the loading machine of CBR test and a compacted sample after loading.

In order to find out the optimum moisture homogenization period (time between material mixing with water and compaction), a series of CBR tests were performed on RCA samples. The water mixed samples were kept in sealed containers in different moisture homogenization periods (e.g. 0, 3, 8 hours) since the main components of crushed concrete; aggregates, cement motar, bricks and sand need specific time period for uniform moisture distribution. The results of these CBR tests are tabulated in Table 6. The three columns show the CBR values for three different curing periods. It is notable in each column that the high CBR values are dominated for the samples having a greater percentage of RM001 since there are more coarse aggregates and absence of bricks and RAP materials. CBR values have been gradually decreased with increasing the portion of RM003 since it presence more fines and course for loss of shear strength of compacted materials by reducing the friction between interlocking particles.

The samples under ‘No moisture homogenization period’ have given the lowest CBR values since they did not have enough time for homogenization of moisture and therefore lower the compaction and CBR values. 3 hours curing period showed higher CBR values since the materials have taken sufficient time for uniform moisture distribution which helps for proper compaction of the samples. Only RM1-100/RM3-0 and RM1-0/RM3-100 were tested to determine the strength gaining of CBR values after 8 hours curing period. Results show 69% in RM1-100/RM3-0 with slight decrease in CBR. More homogenisation time allows cementation of materials with residual cement that makes material less compactive and as a result decreases in CBR value. RM1-0/RM3-100 shows 53% which indicates 3% rise in CBR. This sample consists of more fines and other constituents which required little more time than 3 hours curing for homogenisation of the moisture. Since this rise in CBR is not a greater value, it is concluded that 3 hours is sufficient for both samples to become saturated with moisture mixing throughout the sample. Three hours curing time was recommended for all the six samples since RM1-100/RM3-0 and RM1-0/RM3-100 represents the primary materials RM001 and RM003 and the rest of the 4 samples are mixture of these two. Therefore 3 hours curing for moisture homogenization was followed for curing the next CBR test series.

	
(a)	(b)

Fig. 5 (a) CBR test machine and (b) sample after CBR test

Table 6 Variation of CBR values with different moisture homogenization periods

Sample Type	CBR %		
	No moisture homogenization period	3 hrs moisture homogenization period	*8 hrs moisture homogenization period
RM1-100/RM3-0	61	74	69
RM1-80/RM3-20	56	63	-
RM1-60/RM3-40	55	66	-
RM1-40/RM3-60	50	61	-
RM1-20/RM3-80	48	60	-
RM1-0/RM3-100	46	50	53

*CBR was conducted only for two samples to observe the strength gaining pattern

3.4.1 CBR test for unsoaked samples

Next CBR test series was conducted to investigate the effects of unsoaked curing periods of the compacted samples on CBR values. Each sample was prepared following the 3 hours curing period and followed standard compaction procedure. The compacted samples were cured (unsoaked) in sealed containers for different periods (e.g. 0, 4 and 8 days) with 4.5kg surcharged load before testing. The variations of CBR values with curing periods for each RCA are shown in Table 7. For the first test program, there was not a curing period for compacted samples and then 4 days curing for compacted samples were followed to compare with the 4 days soaked CBR test results. Next, 8 days curing period for compacted samples were applied to observe the strength gaining with time. The CBR values in each column are gradually decreased with increasing the portion of RM003 (Discussed in section 3.4). The results show 4-days curing period is optimum for the compacted samples and the 8-days curing results show that the strength has become steady state. The compacted RCA samples have been strengthened with cementation of the materials and the compacted particles have gained their maximum friction between interlocking particles within first 4-days and then have become steady beyond that. Therefore it shows almost similar CBR values after 8-days curing.

Table 7 CBR Values for Different Curing Period of Compacted Samples

Sample Type		CBR %	
	No curing period for compacted sample	Mixture-3 hrs curing & compacted sample cured 4days	Mixture-3 hrs curing & compacted sample cured 8days
RM1-100/RM3-0	74	81	78
RM1-80/RM3-20	63	77	75
RM1-60/RM3-40	66	74	75
RM1-40/RM3-60	61	63	64
RM1-20/RM3-80	60	60	60
RM1-0/RM3-100	50	58	55

3.4.2 CBR test for soaked samples

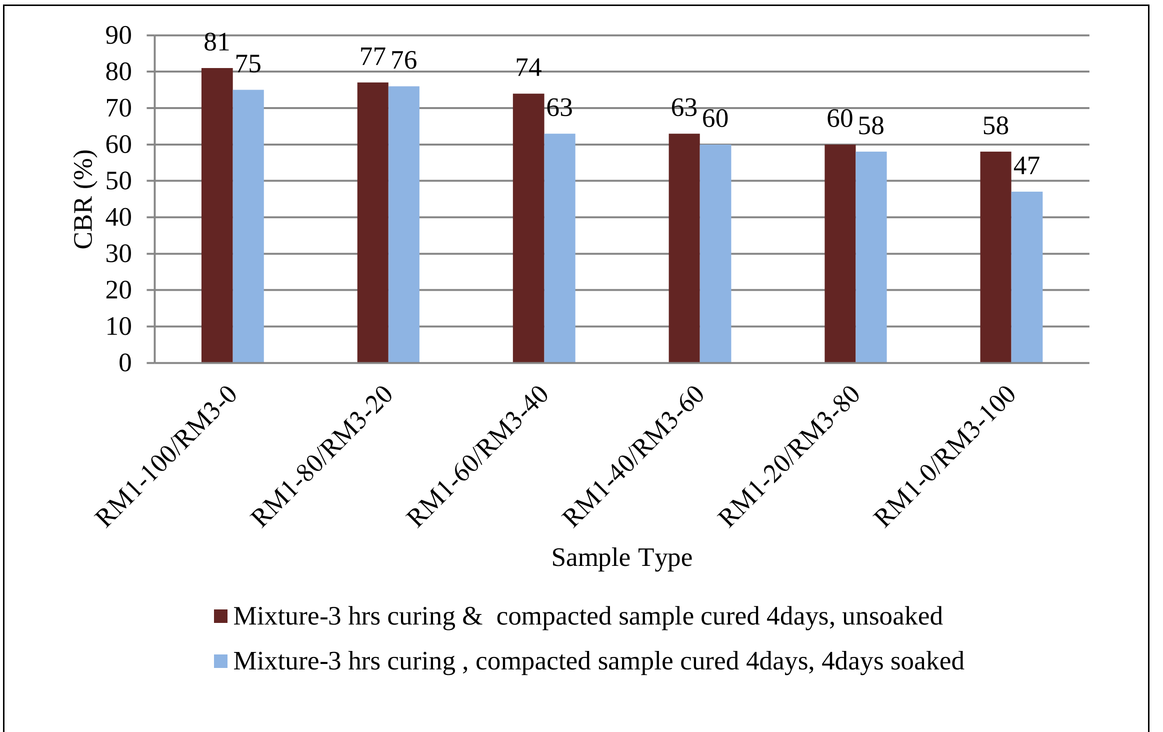

Fig. 6 Summary of CBR values for best unsoaked and soaked results

Testing the CBR values of pavement materials after soaking is more significant to observe the strength of materials under fully saturated condition. This is highly applicable in selecting material and designing pavement for flood. The soaked and the unsoaked CBR values which were obtained for each RCA sample cured for 3 hours after mixing and 4 days after compaction are shown in Fig. 6. For the soaked test, the samples were kept inundated in water for 4 days with 4.5kg surcharged load prior to testing. It shows that soaked CBR values are slightly less than the unsoaked values since the presence of water reduces the inter-particle friction and also high degree of saturation produce high pore-water pressure and cause for low shear strength (Voung *et al.* 2008).

The Department of Main Roads in Queensland has introduced standard limit for minimum soaked CBR values for different pavement layers in different traffic volume roads (Table 3). According to them, none of the sample fulfils the minimum standard CBR value of base layer material in high traffic volume roads (more than 10^6 equivalent standard axle (ESA) repetitions) (MainRoads 2010). The first three samples are in the range of Material type 2.2 which is for base layer in roads with design traffic less than 10^6 ESAs. Other three samples are suitable for sub-base layers in Roads with design traffic equal to or exceeding 10^6 ESAs.

3.4.3 Unconfined Compressive Strength

Unconfined compressive strength (UCS) of a particular material is a significant factor to estimate the bearing capacity in unconfined situation. Conversely, UCS test is used to determine the modulus properties of materials by examining the response of the axial strain of the sample under loading (Yılmaz and Sendır 2002). This is a commonly used test for the modified pavement materials to determine the relative response of granular material to chemical binder stabilization even the CBR test is not used to evaluate the responses of chemical binders in granular materials (Andrews and Group 2006).

In this test series UCS test was performed as specified in AS5101.4-2008 (Australia 2008b) for compacted materials to determine the strength properties. The specimens were prepared at their respective OMC and MDD by applying standard compaction effort. The compacted samples had slightly overtaken the OMC level of each specimen and therefore the MDDs were slightly decreased in the samples. Water mixed samples were cured in sealed containers for 3 hours for equally homogenisation of the moisture and then the compacted samples were cured 4 days in sealed containers prior to the test performed. These curing time periods were based on the best curing time periods for the RCA samples which were revealed through CBR test series (section 3.4 and 3.4.1). Figs. 7(a)-(b) show a UCS sample before and after loading.

As shown in Table 8, UCS value of RCA decreases with increase in RM003 percentage. It is possible to have more residual cement in RM001 than RM003. The residual cement can act as bonding agent among aggregates and give high strength to the sample. Therefore, the higher residual cement content (RM001) is greater the strength of RCA. The increase in RM003 causes on increase in fines particles, possible brick and RAP in RCA and those reduce the friction of interlocking particles and hence lower the load bearing and strength of the compacted samples.

The specified UCS value for base layer material is 0.7-1.5 MPa after the addition of cementitious binders, lime or chemical binders (Australia 2008a). UCS of pavement materials upgrades greater than 1.5 MPa by adding greater quantities of cementitious binder and bituminous binders when higher stiffness is required to provide tensile resistance in base layer (Andrews and Group 2006). The first two samples have UCS 0.45 and 0.44 MPa respectively and can predict the possibility to improve their UCS than 0.7 MPa by adding little quantities of binders as required. It is possible to apply for the other samples as well to add more binders to gain required compressive strength.

	Failure plane 
(a)	(b)
Fig. 7 UCS sample 'RM1-100/RM3-0' (a) before and (b) after test	

Table 8 Unconfined Compressive Strength Values of Compacted Samples

Sample Type	UCS (MPa)
RM1-100/RM3-0	0.4504
RM1-80/RM3-20	0.4365
RM1-60/RM3-40	0.3811
RM1-40/RM3-60	0.3234
RM1-20/RM3-80	0.3014
RM1-0/RM3-100	0.2772

4. Conclusions

Following conclusions can be made for RCA samples prepared by blending two primary crushed concrete products named RM001 and RM003. The test results of six RCA samples (Table 2) are compared with the pavement materials used in state of Queensland, Australia. The comparative standard materials, "Material type 2.1, 2.2, 2.3, 2.4, 2.5" are shown in Table 3 with their descriptions.

- The particle size distribution curves are remaining reasonably well graded before and after compaction of the six samples. However the comparisons of the curves of RCA samples reveal the lack of coarser particles. Six RCA samples are shown their PSD in between Material type 2.1 and Material type 2.2.
- Plasticity index of RCA fines (< 0.425 mm) indicates low plastic properties alike the high quality pavement materials (Crushed Rhyolite and Hornfels) (Jameson *et al.* 2010).

- The proctor compaction test gave relatively higher water absorption for maximum dry density. The high quality base layer crushed aggregates like Rhyolite, Hornfels, Limestones show relatively lower OMC values and they are 5.8, 6.5, 6.5 % respectively (Jameson *et al.* 2010). Both maximum dry density and optimum moisture content increase with increasing the RM003 portion. However, the density varied in a small range giving the lowest value for 'RM1-100/RM3-0' which represents only crushed concrete aggregate.
- RCA require specific time period to optimum the strength in CBR test. With the results, it is possible to conclude the adequate curing time for strength gaining as 3 hours curing after water mixing and 4 days curing after compaction.
- None of the sample has the minimum standard soaked CBR value for base layer material in high traffic volume roads. The first three samples; RM1-100/RM3-0, RM1-80/RM3-20 and RM1-60/RM3-40 samples are showing appropriate CBR strength for use as a base aggregate in roads with design traffic less than 10^6 ESAs. Other three samples are suitable for sub-base layers in roads with design traffic equal to or exceeding 10^6 ESAs.
- The unconfined compressive strength of the six RCA samples did not show the minimum required value which is expected as 0.7 MPa in base layer materials. However it can be improved by adding binders in different quantities for the six samples.
- However, the CBR and UCS results were affected by higher moisture contents which were the achieved moisture levels were slightly over the corresponding OMC values. Therefore, it can be expected higher CBR and UCS results at or below the OMCs of the samples since these materials are highly sensitive in moisture.

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Figures

Original Image files

1. Original source – Pictures were captured by the corresponding author

	
(a)	(b)
Fig. 1 RCA materials (a) RM001 and (b) RM003	

2. Original source – Graphs were drawn by the corresponding author

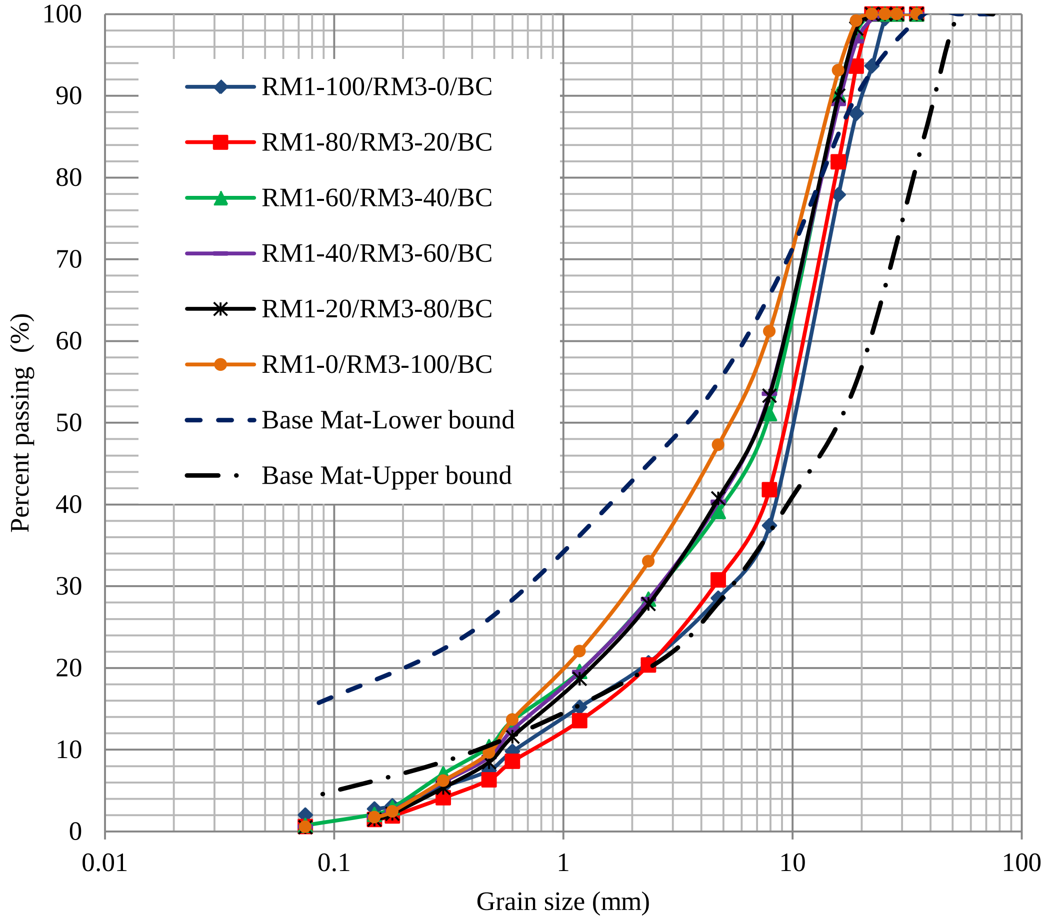

Fig. 2 Gradation curves for six samples and maximum & minimum curves of subtype 2.1 materials

3. Original source – Graphs were drawn by the corresponding author

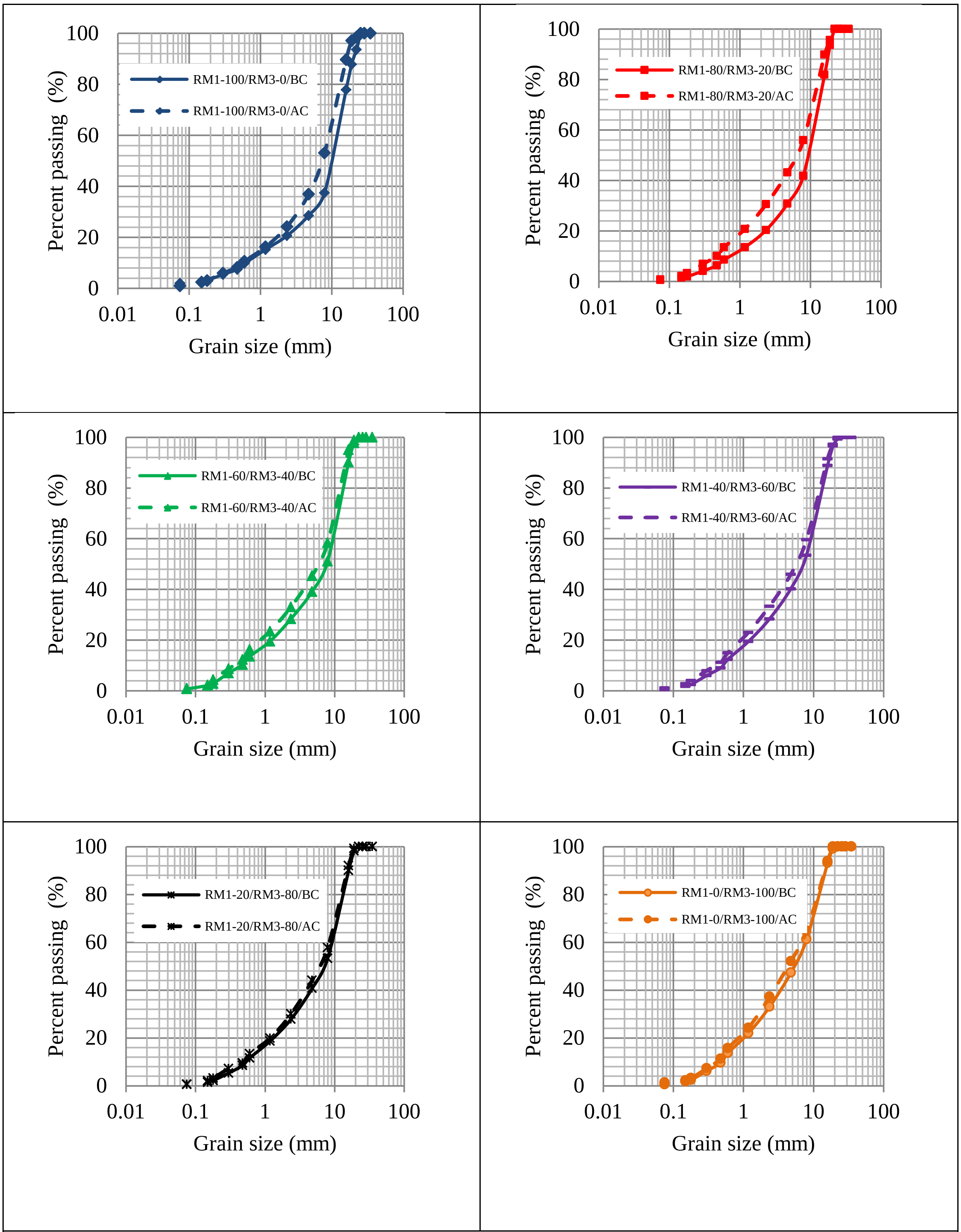

Fig. 3 Gradation curves for six samples prior to and after compaction

4. Original source – Graphs were drawn by the corresponding author

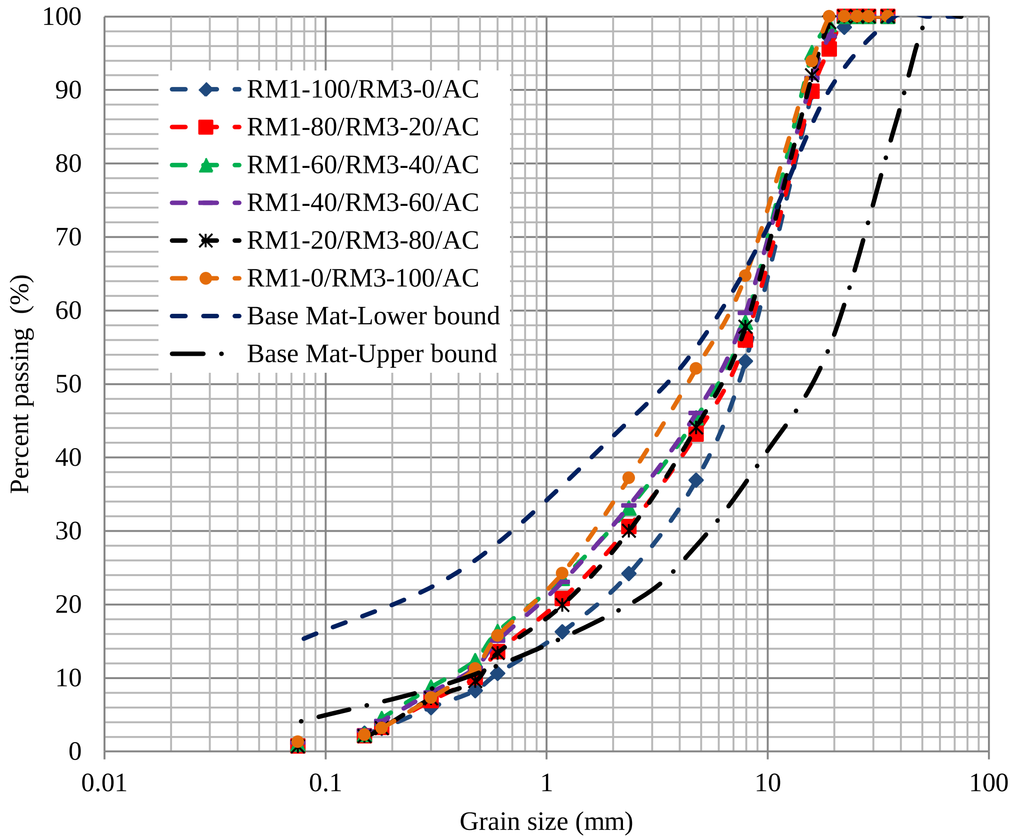

Fig. 4 Gradation curves for six samples after compaction with maximum & minimum curves of subtype 2.1 materials

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(a) (b)

Fig. 5 (a) CBR test machine and (b) sample after CBR test

6. Original source – Graphs were drawn by the corresponding author

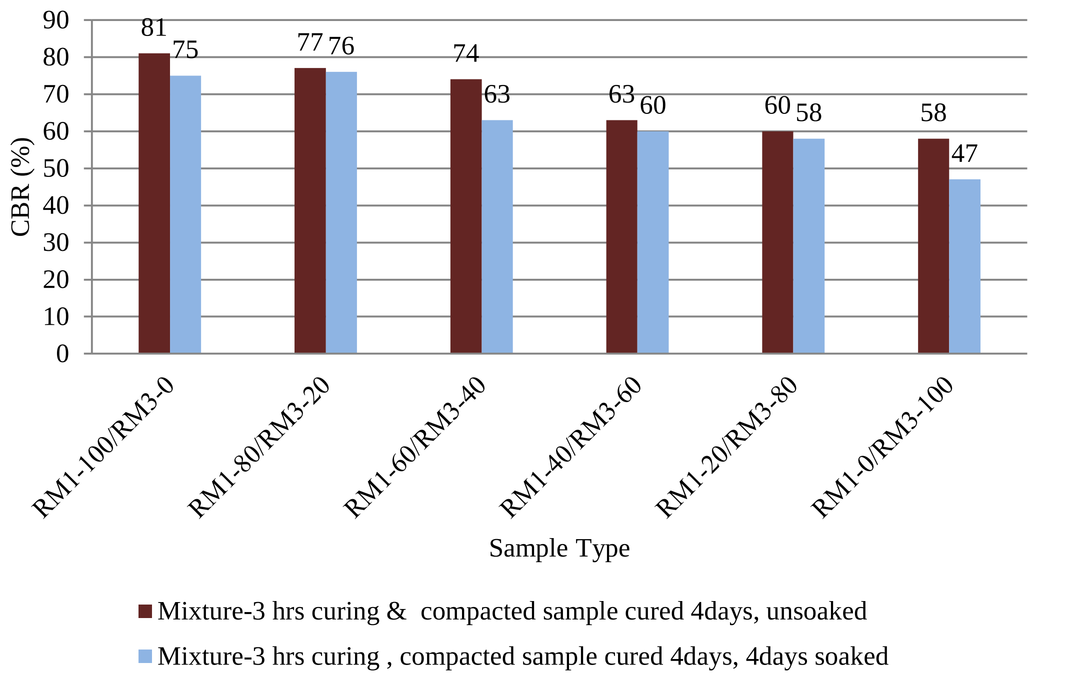
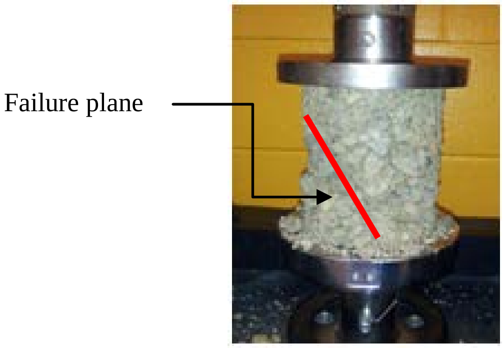


Fig. 6 Summary of CBR values for best unsoaked and soaked results

7. Original source – Pictures were captured by the corresponding author



(a)	(b)

Fig. 7 UCS sample 'RM1-100/RM3-0' (a) before and (b) after test